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Transducer Power Output Obtained from Near-Field Pressure Amplitude and Phase Measurements

February 1, 1963

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Transducer Power Output Obtained from Near-Field Pressure Amplitude and Phase Measurements

By F. B. Stumpf

ORDNANCE RESEARCH LABORATORY
The Pennsylvania State University
University Park, Pennsylvania

February 1, 1963

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Abstract

THE CALCULATION of acoustic power from near-field measurements of piston-type transducers is described, and the results are compared with those calculated from far-field measurements under the same conditions. The near-field measurements, which are required when transducers are calibrated in small-volume pressure tanks, are of two types: axial-pressure measurements, and radial-pressure measurements in a plane near the active face. It is shown that the axial-pressure method is superior for reasons of simplicity in measurement and calculation.

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List of Illustrations

Transducer Power Output Obtained from Near-Field Pressure Amplitude and Phase Measurements

Introduction

FAR-FIELD measurements of transducer acoustic radiation are not possible under certain conditions. When the transducer is calibrated in a small-volume pressure tank, for instance, space limitations prevent far-field measurements, and near-field measurements must be made. This report describes the calculation of acoustic power from near-field measurements of a magnetostrictive plane array in open water at the Ordnance Research Laboratory Calibration Station at Black Moshannon. The criterion by which the near-field method is judged is that the acoustic power obtained must be close to that calculated from the far-field directivity pattern.

Measurement of the Near-Field Axial- and Radial-Pressure Amplitudes and Radial-Pressure Phase

Figure 1 shows the experimental arrangement used to determine the amplitude and phase of the acoustic pressure. The projector was a magnetostrictive plane array driven at 20.5 kc, and the radius of the active area was 6.9 in. A probe hydrophone (Atlantic Research Corporation BC-10) was moved along a diameter in a plane parallel to the face of the transducer at a distance 1 in. from the ρc rubber surface, or 2 in. from the active elements. Note that 2.9 in. is the wavelength of 20.5-kc sound in fresh water at 23 deg C - the conditions for the measurements. The output of the probe was fed into a General Radio 1551-C sound level meter, which gave the relative

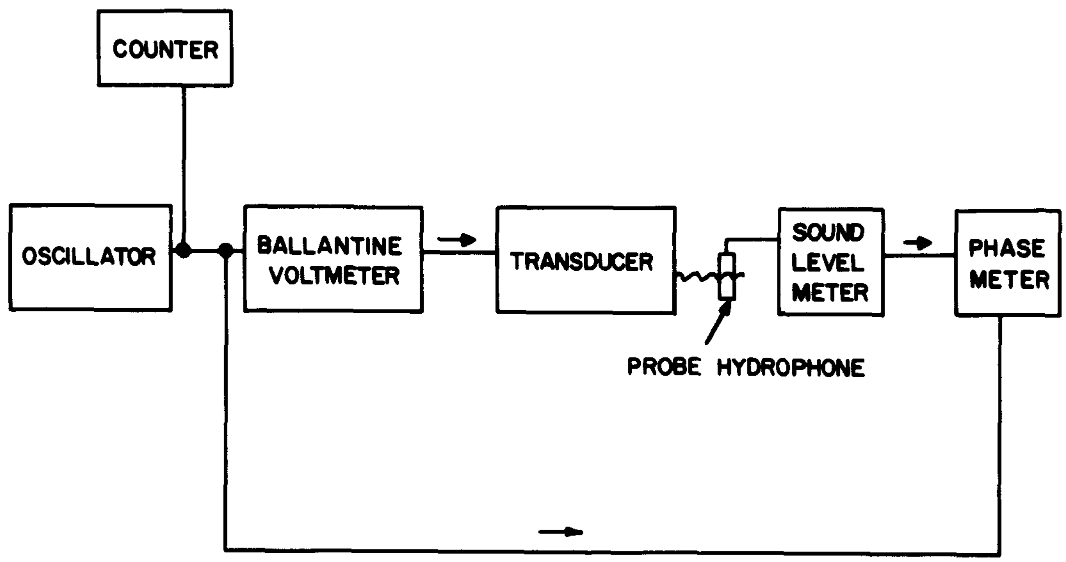

Fig. 1 - Block Diagram of Equipment Required for Near-Field Pressure Measurements

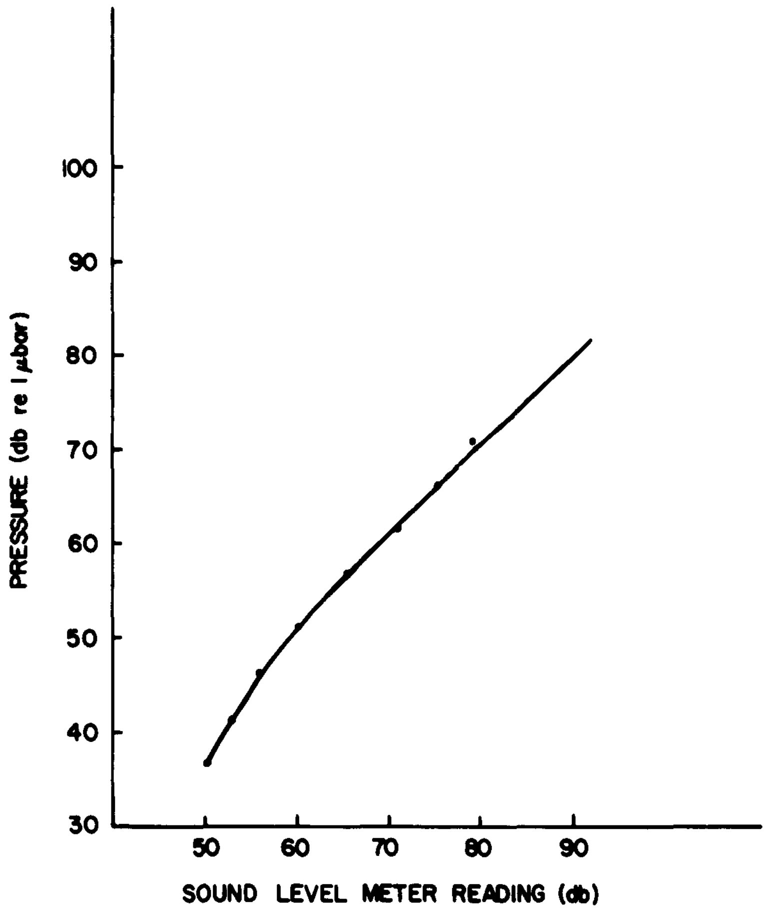

Fig. 2 - Calibration of General Radio Sound Level Meter 1551-C with Atlantic Research Probe BC-10

pressure amplitude. It was necessary to calibrate the probe and sound level meter system by reference to a known pressure field to obtain the actual acoustic pressure. The calibration curve is given in Fig. 2. The signal from the sound level meter was fed into the Ad Yu Type 202 Vectorlyzer and compared with the signal from the oscillator to determine the phase of the pressure. This led directly to the phase difference between the measured pressure values. For a plane wave, the phase would be the same for all points.

The crosstalk was found to be from 30 to 35 db below the level measured across the active face of the transducer. This value was obtained with the probe covered with Cell-Tite neoprene, and indicates that the values measured to a distance of approximately 16 in. are well above background noise.

For the axial-pressure measurements, the BC-10 probe was moved along the axis of the transducer from the ρc rubber face to a distance of 84 in. No phase measurements were taken in this case.

Radial-Pressure Data and Physical Interpretation

Figure 3 shows the corrected pressure amplitude in db relative to 1 μbar plotted against distance along the diameter. It can be seen that there are two peaks, near the edges of the active area, approximately 2 db above a nearly constant level across the face. Furthermore, the fall-off beyond the edges is approximately 12 to 13 db per doubling of distance. These results agree qualitatively with the near-field pressure plots of Grossmann (1),* which show the near-field isobars for a rigid piston with a diameter-to-wavelength ratio (D/λ) of 3.5. In a plane at a distance of nearly one wavelength from the piston, the pressure as a function of radial distance given by Grossmann shows one peak near each edge.

Figure 4 is a plot of the phase of the pressure vs radial distance as measured on the Vectorlyzer. The range in phase values across the face is approximately 50 deg, or slightly greater than $\lambda/10$. The phase changes rapidly beyond the edges.

The approximate agreement of the near-field pressure amplitude with Grossmann's calculated values (1) for a rigid circular piston with D/λ ratio of 3.5 suggests that the radiation from the ORL transducer approaches that of a rigid circular piston with a D/λ ratio between 4 and 5 (actual ratio is 13.75/2.9 = 4.8)** in an infinite rigid baffle. The far-field directivity pattern also supports this physical interpretation. For example, the beam width of the main lobe for a rigid circular piston ($D/\lambda = 4.8$) is nearly 30 deg, as shown in reference 3; and the number of side lobes, based on the pressure distribution at the face, is predicted to be 10 (see reference 3). The measured far-field directivity pattern showed that the main lobe was confined within an angle of approximately 30 deg and that the number of side lobes was 10 or 11.

Derivation of Approximate Expression for Acoustic Power from Near-Field Radial-Pressure Measurements

The equation for intensity in a given direction at a point must be used to obtain an approximate expression of the power:

$$I = \frac{\int_0^T p \cos \omega t \; v \cos(\omega t + \phi)\, dt}{T}, \qquad (1)$$

where I is the intensity, T is the period, p is the pressure amplitude, v is the velocity amplitude, ω is $2\pi f$, and ϕ is the phase angle between the pressure and velocity. If it can be assumed that there is an equivalent average pressure amplitude (p) and velocity amplitude (v) over the plane at $2\lambda/3$ distance from the active face and that the phase (ϕ) is nearly the same for all points in this plane, then this intensity expression can be applied over all points in the measurement plane to determine the power. Therefore,

$$W = I A = \frac{A\, p\, v \int_0^T \cos \omega t \, \cos(\omega t + \phi)\, dt}{T}, \qquad (2)$$

where W is the acoustic power, and A is the active face area. Since the value of the integral in equation 2 divided by T is $\cos \phi/2$,

$$W = \frac{A\, p\, v \cos \phi}{2}. \qquad (3)$$

*Numbers in parentheses refer to References at the end of this report.

**Since the array is mounted in the end of a cylindrical housing, it might be thought that this approximates more nearly the case of a rigid circular piston in a tube (2). However, for large D/λ, it can be seen that the radiation approaches that for the rigid circular piston in a rigid baffle.

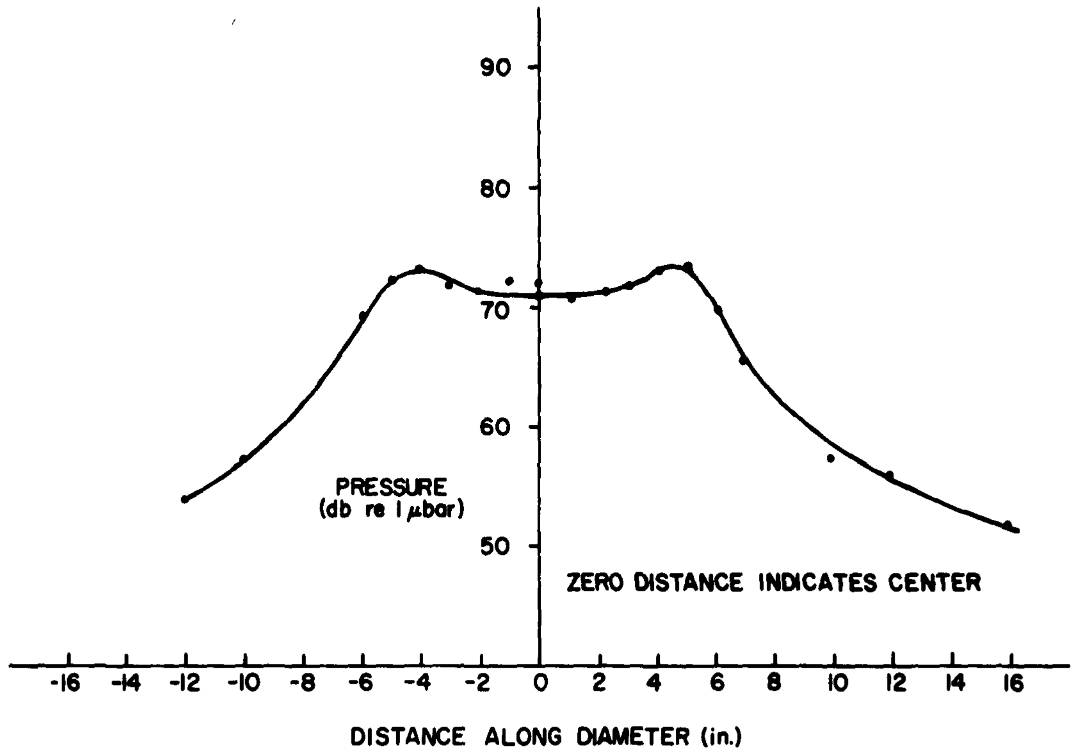

Fig. 3 - Pressure along Diameter of Transducer at $2\lambda/3$ from Active Face

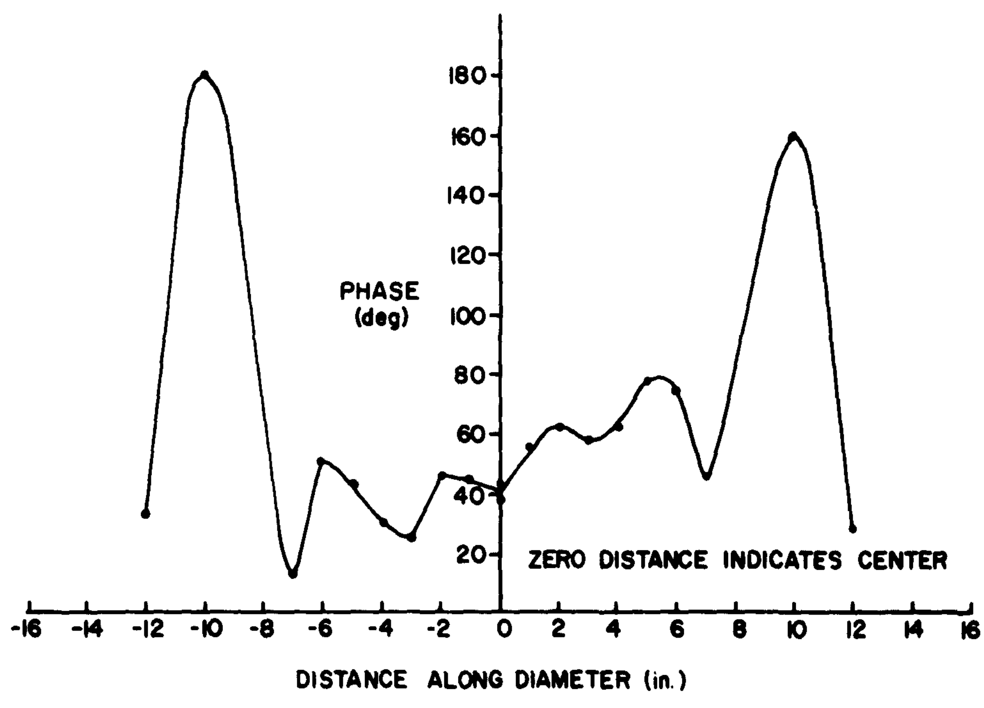

Fig. 4 - Phase of Pressure along Diameter of Transducer at $2\lambda/3$ from Active Face

According to the definition for rms values, $p_{rms} = p/\sqrt{2}$ and $v_{rms} = v/\sqrt{2}$. If p_{rms} is designated by P and v_{rms} by V,

$$W = A P V \cos \phi \quad (4)$$

Furthermore, the amplitude of the acoustic impedance, $|Z|$, is written as

$$|Z| = P/V \, , \quad (5)$$

which allows W to be written as

$$W = \frac{P^2 \, A \cos \phi}{|Z|} \, . \quad (6)$$

But

$$|Z| = (R^2 + X^2)^{1/2} = R\left[1 + (X^2/R^2)\right]^{1/2} = R(1 + \tan^2 \phi)^{1/2} \, .$$

From trigonometric identities,

$$(1 + \tan^2 \phi)^{1/2} = (\sec^2 \phi)^{1/2} = \sec \phi = 1/\cos \phi \, .$$

Therefore, when $|Z| = R/\cos \phi$ is substituted,

$$W = \frac{P^2 A \cos^2 \phi}{R} \, . \quad (7)$$

Since R is nearly ρc,

$$W = \frac{P^2 A}{\rho c} \cos^2 \phi \, . \quad (8)$$

Since the average values for P and ϕ are used in the calculation, they are denoted with overlines. Therefore,

$$W = \frac{(\bar{P})^2 A}{\rho c} \cos^2 \bar{\phi} \quad (9)$$

Note, however, that some questionable assumptions had to be made to obtain this equation and, hence, its usefulness is limited.

Calculation of Acoustic Power from Near-Field Radial-Pressure Data

The following values were used to calculate the power in equation 9: $\rho c = 1.48 \times 10^5$ gm per cm^2 sec, and A = area of active face of the transducer = 148 in.^{2} = 945 cm^2. The total area is obtained by addition of the areas associated with all the stacks making up the array. The average pressure reading for the area in the measurement plane equal to the active area is substituted for

$\bar{P}$. This will be an rms reading, since the sound level meter reads rms values. The average pressure is obtained from

$$\bar{P} = \frac{\int_0^{6.88\ \text{in.}} P(r)\, 2\pi r\ dr}{A}, \qquad 10$$

and is based on the assumption that there is axial symmetry in the measurement plane (parallel to the face), the pressure being dependent on the radial distance, r, only. The value for $\bar{P}$ was obtained from Fig. 5, in which r P(r) is plotted against r. There is some difficulty in knowing which area of Fig. 5 to use. Note that there is a considerable rP product outside the active face but that it also represents great changes in phase, which present a problem. A planimeter was used to obtain the area under the curve, which corresponds to the integral in equation 10. The value obtained was an average power of 3260 μbar. The only quantity left is ϕ; but, unfortunately, there appears to be no very satisfactory way to measure the phase angle between the pressure and velocity. An attempt (4) was made to measure pressure and velocity simultaneously, in the case of Clapp and Firestone's acoustic wattmeter, but this was not entirely satisfactory.

A rather crude approximation would be to neglect the $\cos^2\phi$ term (that is, to let $\phi \approx 0$) and to say, at least for an order-of-magnitude calculation, that W is given by

$$W \approx \frac{(\bar{P})^2 A}{\rho c}. \qquad 11$$

When the values for these quantities (P = 3260 μbar and A = 945 cm^2) are substituted and converted to mks units,

$$W \approx \frac{(3260)^2 \times 945 \times 10^{-7}}{1.48 \times 10^5}\ \text{watts} \approx 6.8 \times 10^{-3}\ \text{watts}. \qquad 12$$

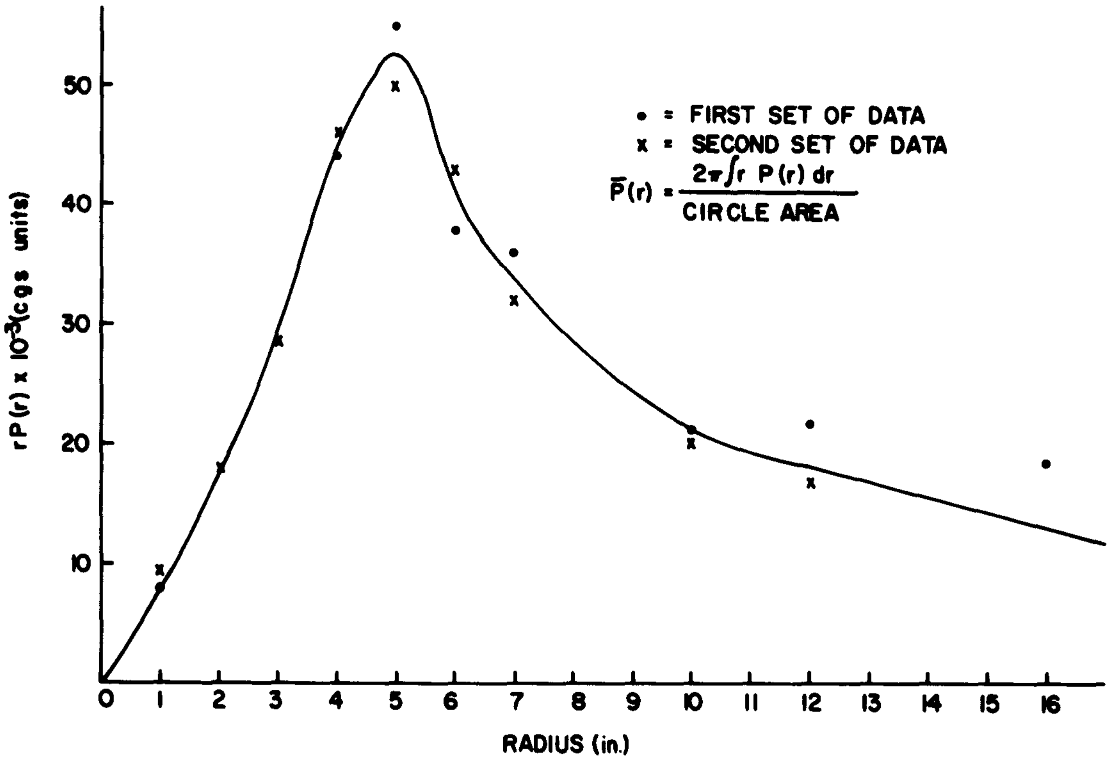

Fig. 5 - Plot of $rP(r) \times 10^{-3}$ vs Radius at $2\lambda/3$ from Active Face

To check this near-field value, a far-field power value was obtained from far-field measurements. The procedure used was to plot the directivity pattern on Kendig-Mueser paper (5) and to measure the area under the curve by means of a planimeter. This area is related to the directivity factor (D. F.). The pressure on the axis was also measured. Then the following expression for the D. F. was used:

$$\mathrm{D\,F} = \frac{P^2/\rho c}{W/4\pi x^2} , \qquad 13$$

where P is the axial pressure at a distance x, and W is the acoustic power. The value obtained with a D. F. of 220 from a Kendig-Mueser plot, a distance (x) of 72 in., and an axial pressure (P) of 2200 μbar was W = 6.0 x 10^{-3} watts. Therefore, the difference in decibels between the near-field and far-field powers is 0.5 db, since 10 log 6.8/6.0 = 10 log 1.13 $\approx$ 0.5 db.

This method is not completely satisfactory because of the problems involved in deriving W, measuring ϕ, and determining the area through which the radiation passes. However, it is interesting to note that this method has some merit if it is interpreted correctly. Later it will be shown that the pressure on the axis varies between maxima and minima and that P_{max} = 6095 μbar. Now, the pressure used to obtain the near-field power value was 3260 μbar $\approx P_{max}/2$, within experimental and graphical error. Therefore, the power expression in equation 12 is nearly $W \approx (P_{max}/2)^2 A/\rho c$, where A = the area of the piston. This is the expression for a plane wave of pressure $P_{max}/2$ confined to an area equal to the area of the piston. This result has been noted in the work of Simmons and Urick (6) and that of Trott (7) on near-field calibrations. This result means that equation 11 is an approximate relationship for obtaining the power. In equation 11, average power is obtained by taking a graphical average, over an area equal to that of the transducer, of the individual pressures measured very near the face. The piston area (A) is equal to the area of the transducer.

Derivation of Expression for Acoustic Power from Axial-Pressure Measurements

If the radiation can be considered as approximately that of a circular piston in an infinite rigid baffle, then the axial pressure will fluctuate in the near field between maxima and minima, as shown in reference 3 (Fig. 3.10), and as obtained from measurements plotted in Fig. 6. The maximum pressure can then be measured and used in the power calculations, as will be shown.

The following expression for the D. F. was used to calculate the power (W):

$$\mathrm{D\,F} = \frac{P^2(x)/\rho c}{W/4\pi x^2} ,$$

or

$$W = \frac{4\pi x^2 P^2(x)}{\rho c\,\mathrm{D\,F}} . \qquad 14$$

Here, P is the pressure at a distance x along the axis of the transducer. The D. F. and P(x) must be known to evaluate this expression.

If the radiation can be considered as nearly that of a rigid circular piston in an infinite rigid baffle, as indicated before, then D. F. is as given by reference 8 (p. 184):

$$\mathrm{D\,F} = \frac{k^2 a^2}{1 - \left[2J_1(2ka)\right]/2ka} . \qquad 15$$

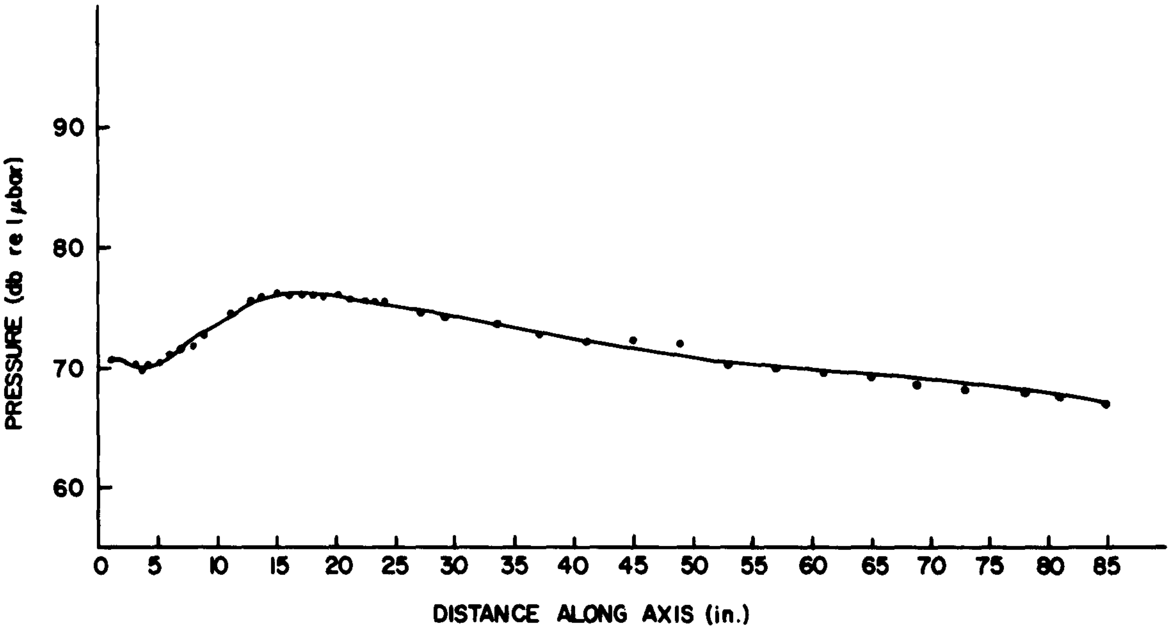

Fig. 6 - Pressure along Transducer Axis

If ka is large compared with 1, $J_1(2ka)$ is very small, and

$$D.F = k^2a^2, \text{ or } k^2D^2/4 , \tag{16}$$

where D is the diameter of the piston.

The axial-pressure expression (see references 9 and 3) for a circular piston is used to calculate P(x):

$$P(x) = P_{max} \sin \frac{k}{2} \left[\left(\frac{D^2}{4} + x^2 \right)^{1/2} - x \right] . \tag{17}$$

The pressure P(x) can be evaluated, after P_{max} is measured, and used directly in equation 14 to obtain W; or, if x is large compared with D, the following approximation can be made by expansion in a binomial series:

$$\left(x^2 + \frac{D^2}{4} \right)^{1/2} - x = \frac{D^2}{8x} - \frac{D^4}{128x^3} \cdots \tag{18}$$

For x >> D^2, the argument of the sine becomes $D^2/8x$, and substitution in equation 17 gives

$$P(x) = P_{max} \sin \frac{k}{2} \frac{D^2}{8x} \tag{19}$$

Since the argument is small, the sine can be replaced by its argument to give

$$P(x) = P_{max} \frac{kD^2}{16x} . \tag{20}$$

The values for D. F. and P(x) can now be substituted in equation 14 to obtain the approximate power expression involving the axial pressure. Therefore,

$$W = \frac{4\pi x^2 P_{max}^2 k^2 D^4}{\rho c \left(\frac{k^2 D^2}{4}\right) 256 x^2} ; \qquad 21$$

or, simplifying,

$$W = \frac{\pi P_{max}^2 D^2}{16 \rho c} = \frac{(P_{max}/2)^2}{\rho c} \frac{\pi D^2}{4} . \qquad 22$$

This equation shows that the power radiated by a circular piston is given by an intensity of the form $P^2/\rho c$ (where $P = P_{max}/2$) over an area equal to the area of the piston. Therefore, an equivalent physical situation for the acoustic power radiated from the magnetostrictive array is that of a plane wave of pressure $P_{max}/2$ confined to an area equal to that of the piston. This was found to be the result when the power was calculated from the near-field pressure data.

Calculation of Acoustic Power from Near-Field Axial-Pressure Data

The calculation of power from near-field axial-pressure data can be divided into two distinct cases: calculation of the power when the radius of the equivalent circular piston is known; and calculation of the power when the radius of the equivalent circular piston is unknown. The first case is the simpler of the two, being merely a matter of substitution in equation 22. The second case involves the concept of effective radius.

ACOUSTIC POWER WHEN RADIUS OF THE EQUIVALENT CIRCULAR PISTON IS KNOWN

When the radiation characteristics of the transducer are nearly equivalent to those of a rigid circular piston in an infinite rigid baffle, the power is obtained by substitution in equation 22. Substitution leads to $W = 6.0 \times 10^{-3}$ watts. Note that 6095 μbar is the P_{max} (obtained from Fig. 6, the pressure-vs-distance curve), and D = 13.75 in. is the diameter corresponding to an area of 148 in.[2] There is no difference between this power and the far-field power (6.0×10^{-3} watts). This is fortuitous since the error in each power value might be as much as 5 to 10 per cent. In this case and the following case, it would be well to check the value for D. F. by far-field measurements in the free field, if possible.

ACOUSTIC POWER WHEN RADIUS OF THE EQUIVALENT CIRCULAR PISTON IS UNKNOWN

When the radiation pattern is known to be approximately that of a circular piston of unknown radius (for example, in an approximately circular array of elements), it is helpful to use the concept of an effective radius. This effective radius can be obtained from the expression for the position of the maxima in the axial pressure given in reference 3 (p. 69):

$$x = \frac{4a^2 - \lambda^2 (2m+1)^2}{4\lambda(2m+1)} . \qquad 23$$

Here, m = 0,1,2,..... For the first maximum (one with the largest x), m = 0. Therefore,

$$x_{m=0} = \frac{4a^2 - \lambda^2}{4\lambda} ; \qquad 24$$

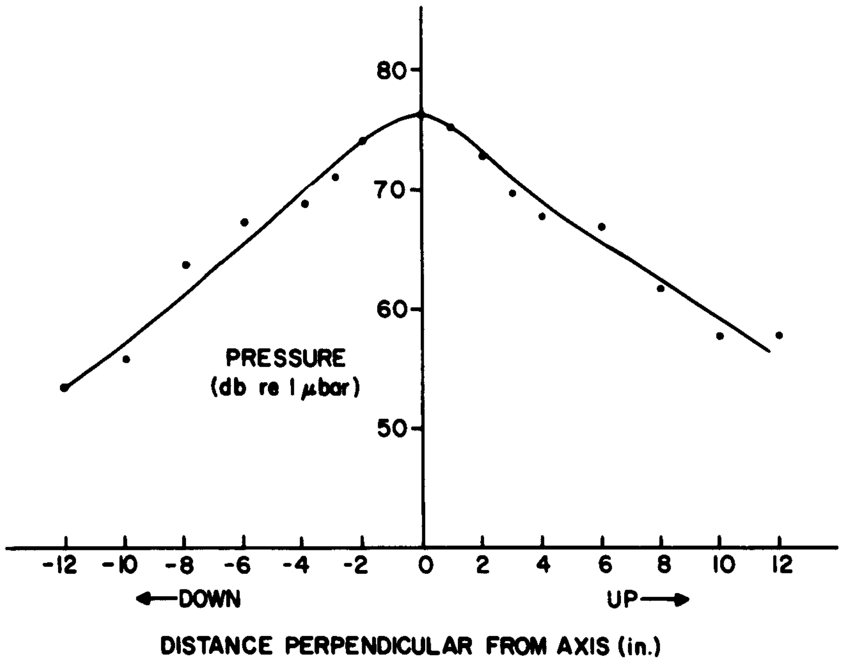

Fig. 7 - Transducer Off-Axis Pressure at 16 In. from Active Face

or, for the effective radius a,

$$a^2 = \frac{4x_{m=0}\lambda + \lambda^2}{4} . \qquad 25$$

When the measured value from Fig. 6 (17 in.) is substituted for $x_{m=0}$, the effective radius is 7.2 in. In this case, it means the effective radius is 7.2 in. as compared to 6.9 in. from measurements of the stack dimensions and spacing. Since the power depends on a^2, the power computed by equation 22 is $(7.2)^2/(6.9)^2 \times 6.0 \times 10^{-3}$, or 6.6×10^{-3} watts.

Since the D. F. for the circular piston of 7.2-in. equivalent radius is k^2a^2, a value of 240 is obtained. This is about 10 per cent higher than the value of 220 obtained from the far-field data.

When the maximum sound pressure is measured along the axis of the transducer, it is important that the probe be accurately moved along the axis. Figure 7 shows the variation of sound pressure with perpendicular distance from the axis when the sound pressure is measured 16 in. from the face of the transducer (17 in. from the active faces of the stacks), the range at which the maximum occurs in Fig. 6.

Conclusions

The data obtained from the two sets of near-field measurements indicate that the radiation of the array is similar to that of a rigid circular piston in an infinite rigid baffle. The D/λ ratio was determined to be nearly 4.8. The calculation of power by means of axial-pressure measurements was found to be superior to the radial-pressure method because (a) it is very difficult to measure the phase angle between the pressure and velocity at each point; (b) it is easier to evaluate the pressure, P_{max}, for the axial-pressure method rather than to obtain an average for the radial-pressure measurements; and (c) some rather limiting assumptions had to be made in the theoretical development of the radial-pressure method. For the axial-pressure function, the approximation of the acoustic power is that for a plane wave intensity associated with $P_{max}/2$ through an area equal to that of the piston. A similar result was obtained when the radial-pressure method was used.

It should be possible to extend the axial-pressure method to include rectangular pistons since this case has been solved by Stenzel (10). Stenzel presents the analytical expression for the axial pressure and the corresponding curves.

A cylindrical tank with absorptive lining and an adjustable probe hydrophone could be built for transducer power measurements at high hydrostatic pressures. The probe hydrophone could be mounted on a rod and moved along the axis of the tank between the hydrophone and the opposite end of the tank. If reflections from the walls are excessive, a pulse method could be used for the measurements. A study of the change in axial-pressure characteristics as the hydrostatic pressure is varied could lead to important conclusions concerning transducer performance.

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